

Lattice Phenomenology with domain wall quarks: Hunting New Physics with the Lattice

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Outline

- Why lattice is needed
- Exact Chiral Symmetry on the Lattice
- Update: B_K
- **Relevance of lattice to the LHC era**
- Recent applications
- Summary & Outlook

Due to the non-perturbative nature of low energy QCD, many experimental results, often attained at enormous cost cannot be used effectively to test the Standard Model unless accurate values of hadronic matrix elements are known; lattice is the only reliable tool for such calculations

$$\langle K | [\bar{s} \gamma_\mu (1 - \gamma_5) d] | K \rangle / \frac{8}{3} f_K^2 m_K^2$$

$|\epsilon_K|$ (BNL '64; Christenson et al), provides a
CLASSIC EXAMPLE.

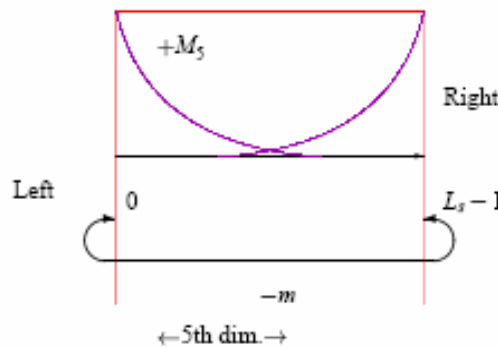
$$|\epsilon_K| = \hat{B}_K C_K \lambda^6 A^2 \bar{\eta} \{ \eta_1 S(x_c) + \eta_2 S(x_t) [A^2 \lambda^4 (1 - \bar{\rho})] + \eta_3 S(x_c, x_t) \} \quad C_K = \frac{G_F^2 f_K^2 m_K m_W^2}{6\sqrt{2}\pi^2 \Delta m_K}$$

The experimentally known value $|\epsilon_K| = 2.27 \times 10^{-3}$ can be used to extract information on the poorly known SM parameters $\bar{\rho}$ and $\bar{\eta}$, once the non-perturbative quantity, B_K becomes known, as everything else on the RHS is known quite well.

EXACT CHIRAL SYMMETRY ON THE LATTICE

Conventional fermions do not preserve chiral-flavor symmetry on the lattice (Nielsen - Ninomiya Theorem)
 $\Rightarrow \Delta S = 1, \Delta I = 1/2$ case mixing with lower dim. (power-divergent) operators & or mixing of 4-quark operators with wrong chirality ones makes lattice study of $K - \pi$ physics virtually impossible.

Domain Wall Fermions (Kaplan, Shamir, Narayanan and Neuberger)

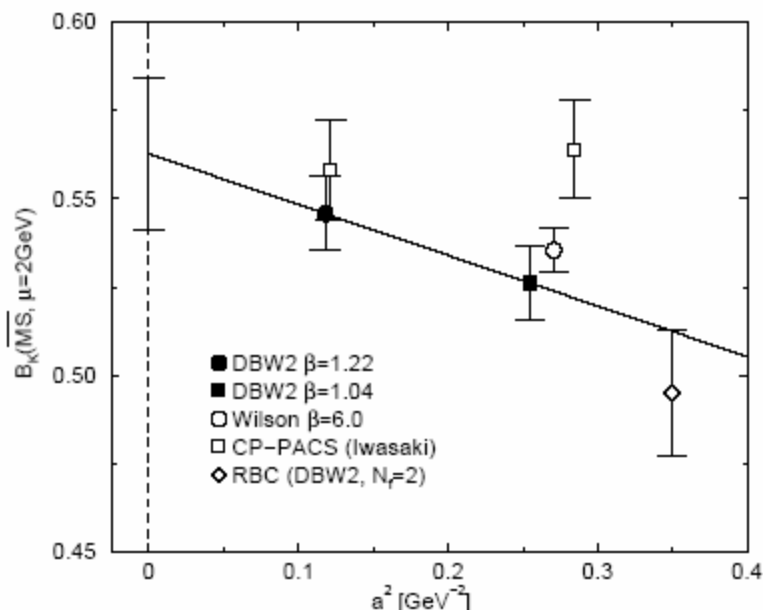


Practical viability of DWF for QCD demonstrated (96-97) Tom Blum & A. S.

Chiral symmetry on the lattice, $a \neq 0$! Huge improvement

\Rightarrow Now widespread use at BNL and elsewhere

RBC effort (~'98-'05 with QCDSF), PRD'05; Quenched & $n_f=2$ dyn.
 $B_K(2\text{ GeV}) = 0.563(21)(39)(30)$
 Last error due quenching using $n_f=2$ dyn.



**RBC has reduced
quenching error by ~
factor of 3
and finds lower central
value by ~ 2 σ
-> tends to increase η**

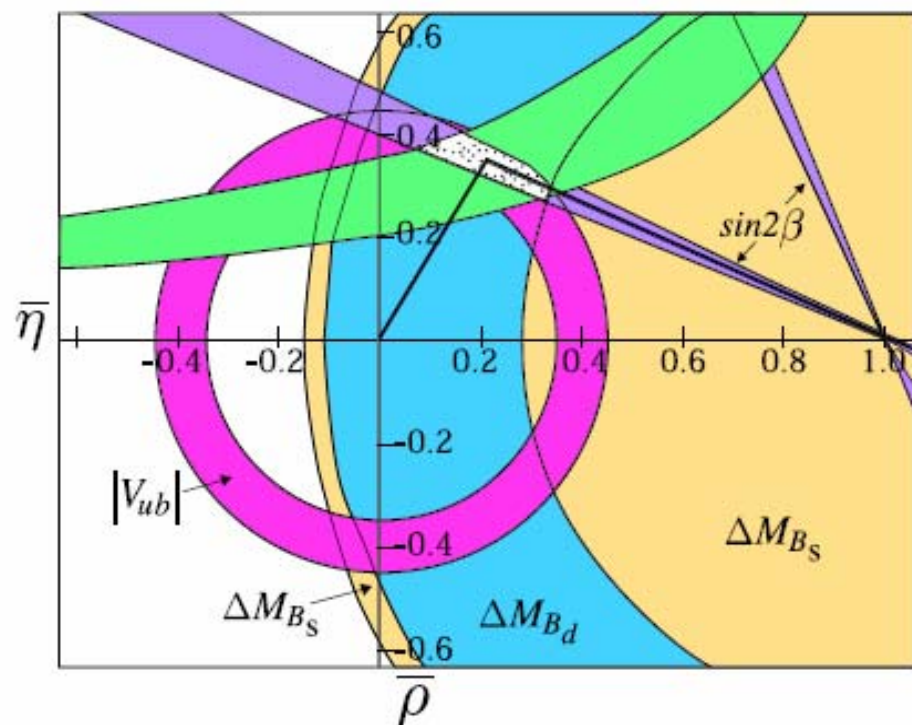
FIG. 32: Summary of our results for $B_K^{\overline{\text{MS}}\text{NDR}}(\mu = 2\text{ GeV})$ renormalized with $N_f = 0$ as a function of the lattice spacing squared. The filled circles are our results and the open symbols are quoted from previous works [21, 30]. Open diamond is the $N_f = 2$ result obtained in Ref. [31].

**To be compared with JLQCD, PRL '98 (staggered, quenched)
 $B_K(2\text{ GeV}) = 0.628(42)$; guess estimate of quenching error= (110) used widely**

Kaon Bag Parameter

Important to CP Violation

Errors in the determination of ϵ are now dominated by uncertainty in the value of B_K .



Existing expts. + lattice $\rightarrow \sin 2\beta = 0.70(10)$
Through direct measurement B-factories give $\sin 2\beta = 0.685(32)$..striking confirmation of CKM paradigm. CKM-phase is dominant contributor to observed CPV in K, B..

Lattice weak matrix element effort helps attain a milestone in our understanding of CPV phenomena

Constraint by ϵ denoted by green hyperbolic bands.

- ◆ Product of B meson decay constant f_B and CKM matrix element $|V_{ub}|$

$$f_B \cdot |V_{ub}| = (7.73^{+1.24}_{-1.02}(\text{stat})^{+0.66}_{-0.58}(\text{syst})) \times 10^{-4} \text{ GeV}$$

G_F	1.16639×10^{-5}	GeV^{-2}
τ_B	$(1.643 \pm 0.010) \times 10^{-12}$	s
m_B	5.279	GeV
m_τ	1.77699	GeV

- ◆ Using $|V_{ub}| = (4.38 \pm 0.33) \cdot 10^{-3}$ from HFAG

$$f_B = 0.176^{+0.028}_{-0.023}(\text{stat})^{+0.020}_{-0.018}(\text{syst}) \text{ GeV}$$

$$f_B = 0.216 \pm 0.022 \text{ GeV (HPQCD)}$$

Phys. Rev. Lett. 95, 212001 (2005)

Bernard, Labrenz & Soni (PRD '94) f_B (quenched) = 187(10)(34)(15) MeV
(Based on Jim Labrenz thesis @BNL)

Brief (~25 years) History of B_K

- ~'83, DGH use K^+ lifetime + LOChPT + SU(3) \rightarrow
 $B_K \sim 0.33$... no error estimate, no scale dependence.
- ~'84 Lattice method for WME born...many attempts
& improvements for B_K evaluations
- ~'98 JLQCD staggered $B_K(2\text{GeV}) = 0.628(42)$ quenched (~110).
- ~'97 1st B_K with DWQ (T.Blum & A.S), 0.628(47) quenched.
- ~'01 RBC B_K with DWQ, quenched = 0.532(11) quenched
- ~'05 **RBC, $nf=2$, dyn. DWQ, $B_K = 0.563(21)(39)(30)$**
- ~'06 Gimnez et al (stagg.) 2+1, $B_K = 0.618(18)(19)(30)(130)$
- ~'08 **Target 2+1 dyn. DWQ, B_K with total error 5%**

Relevance of Lattice to the LHC era

- QCD will be an integral part of any BSM scenario -> need ability for non-perturbative calculations.
- Two illustrations
 - a) B_K
 - b) proton lifetime

RELEVANCE of LQCD to the LHC era.
e.g. B_K (say due SUSY)

$$\underbrace{W \quad \Sigma W}_{SM} + \underbrace{W \quad W}_{SUSY} + SUSY$$

Y.Aoki et al (RBC) '05

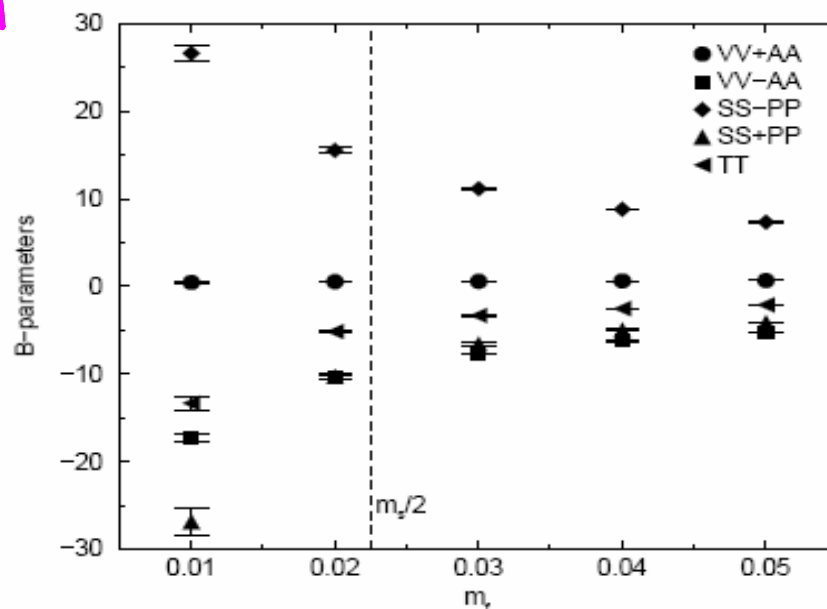
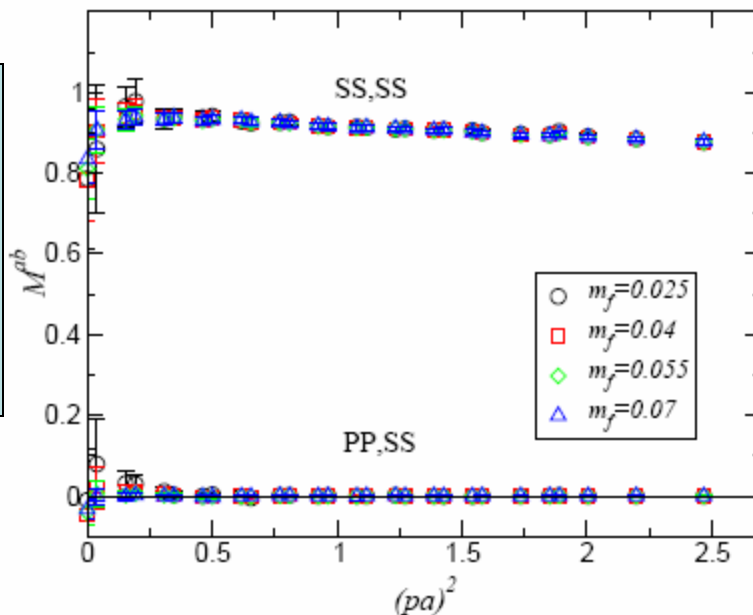


FIG. 31: B-parameters for \mathcal{O}_{VV+AA} (circle), \mathcal{O}_{VV-AA} (square), \mathcal{O}_{SS-PP} (diamond), \mathcal{O}_{SS+PP} (triangle) and \mathcal{O}_{TT} (left-triangle) for DBW2 $\beta = 1.04$ as a function of m_f .

2nd Example: Application of DWQ to $p \rightarrow e\pi$ in GUTs & SUSYGUTs

Aoki, Dawson, Izubuchi
& Soni (RBC) (in prep.)



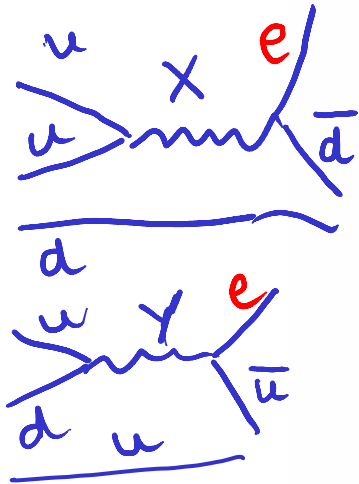
Mixing of operators
with wrong chirality is
completely negligible,
a significant advantage
Of DWQ

FIG. 1: SS and PP projections of the SS operator, $M^{SS,SS}$ and $M^{PP,SS}$ as a function of lattice momentum squared for each quark mass.

Results for LEC's for proton decay

TABLE VI: Comparison of the low energy parameter of the nucleon decay chiral Lagrangian α and β among various QCD model calculation, lattice results in the literatures and the results from this work. Results with QCD model calculations are taken from the compilation by Brodsky et al. [15] In lattice QCD calculations, WF and DWF mean Wilson and domain-wall fermions. Our quenched results are shown with the total error consisting of statistical and systematic errors on the bare matrix element, renormalization constant and scale. The unquenched errors are only statistical.

		$ \alpha \text{ [GeV}^3]$	$ \beta \text{ [GeV}^3]$	
QCD model calculation	Donoghue and Goldwich [10]	0.003		Bag model
	Thomas and McKellar [13]	0.02		Bag model
	Meljanac et al. [11]	0.005		Bag model
	Ioffe [8]	0.009		Sum rule
	Krasnikov et al. [12]	0.006		Sum rule
	Ioffe and Smilga [14]	0.006		Sum rule
	Tomozawa [9]	0.006		Quark model
		0.03		
Lattice QCD	Hara et al. [16]	0.03		WF, $a^{-1} = 1.8 \text{ GeV}$
	Bowler et al. [17]	0.013	0.010	WF, $a^{-1} = 0.9 \text{ GeV}$
	Gavela et al. [18]	0.0056(8)	$\simeq \alpha $	WF, $a^{-1} = 2 \text{ GeV}$
	$N_f = 0$ JLQCD [19]	0.015(1)	0.014(1)	WF, $a^{-1} = 2.3 \text{ GeV}$
	CP-PACS & JLQCD [20]	0.0090(09)(\pm_{19}^6)	0.0096(09)(\pm_{20}^6)	WF, continuum limit
This work		0.0100(19)	0.0108(21)	DWF, $a^{-1} = 1.3 \text{ GeV}$
Lattice QCD	This work	0.0117(21)	0.0117(21)	DWF, $a^{-1} = 1.7 \text{ GeV}$
$N_f = 2$				



First Lattice Calculation of NEDM [with dyn. (2 flavor)DWQ] due to the θ parameter (Blum, Orginos & A.S), PRD'06

TABLE VI: Form factors normalized by the electric form factor of the proton, $G_E(q^2)$ (Equation 33). In the limit $q^2 \rightarrow 0$, the values in the F_2 columns yield the anomalous magnetic moments and in the last two columns, the electric dipole moment of the neutron using currents and projectors defined in Equations 41 and 42. $m_{sea} = 0.03$ (upper) and $m_{sea} = 0.04$ (lower).

q^2 (GeV ²)	$F_1(q^2)/G_E(q^2)$		$F_2(q^2)/G_E(q^2)$		$(F_3(q^2)/2m)/G_E(q^2)$	
	proton	neutron	proton	neutron	neutron	
0.399	1.0784 (63)	-0.034(10)	1.680 (98)	-1.698 (68)	-0.04 (20)	0.49 (45)
0.824	1.183 (15)	-0.1261 (211)	1.90 (12)	-1.827 (82)	0.45 (23)	1.56 (73)
1.183	1.297 (40)	-0.219 (42)	2.15 (23)	-1.90 (15)	-0.08 (36)	-0.74 (1.73)
1.363	1.251 (57)	-0.176 (71)	1.57 (31)	-1.73 (25)	0.02 (53)	-0.39(73)
0.401	1.0695 (42)	-0.045 (7)	1.703 (59)	-1.715 (46)	0.087 (95)	0.12(27)
0.753	1.1349 (89)	-0.081 (13)	1.760 (66)	-1.785 (52)	0.20(10)	-0.18(41)
1.044	1.2181 (223)	-0.102 (27)	2.050 (129)	-2.013 (101)	0.12 (16)	-1.29 (75)
1.538	1.2107 (414)	-0.156 (45)	1.345 (195)	-1.409 (136)	-0.29 (25)	0.55 (38)

$d_N = -0.04(20)\text{-e-}\theta\text{-fm}$; $< 0.02 \text{)-e-}\theta\text{-fm}$This upper bound is a factor of about 4 to 10 higher than phenomenological estimates

Near Future

- **RBC -> [RBC + UKQCD] DWF project**
- **QCDOC at BNL (RBRC) ...~66%**
- **QCDOC at Edinburgh ~50%**
- **QCDOC at BNL (DOE)~30%**
- **Factor of ~20 more computing power over '98-'04(QCDSP)**
- **Note: Lattice will be relevant even in the LHC era**
- **2+1 dynamical DW simulations in progress. Look forward to improved calculations of B_K , ϵ'/ϵ , $Kl3$, NEDM, $p \rightarrow e\pi$ and many other quantities of physical interest.**

Summary & Outlook

I. HET group is involved in diverse areas of HEP, precision EW, flavor, collider, LHC & RHIC phenomenology and in a very strong Lattice gauge effort ; list of recent pubs attached.

II. Overriding concerns:

- 1. NEED MORE POST-DOCS!! (only 2 for next year severely undercuts the capability of the group, esp. in light of the LHC era)**
- 2. Aging of the group**

- M. Creutz, Flavor extrapolations and staggered fermions, hep-lat/0603020.
- M. Creutz, Fun with Dirac eigenvalues, hep-lat/0511052.
- M. Creutz, Hidden symmetries in two dimensional field theory, hep-th/0508116.
- M. Creutz, Isospin breaking and the chiral condensate, hep-lat/0508012.
- M. Creutz, The invariant measure for $SU(N)$, AIP Conf. Proc. 756:466-466, 2005.
- S. Dawson, M.C. Chen, T. Krupovnickas, Higgs Triplets and Limits from Precision Measurements, hep-ph/0604102.
- S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, Hadronic Higgs production with heavy quarks at the Tevatron and the LHC, hep-ph/0603112.
- S. Dawson, Electroweak symmetry breaking Circa 2005, hep-ph/0510385.
- S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, Higgs production in association with bottom quarks at hadron colliders, hep-ph/0508293.
- S. Dawson, M. Chen, T. Krupovnickas, Constraining new models with precision electroweak data, hep-ph/0504286.
- W. Kilgore et al., Les Houches Physics at TeV Colliders 2005, Standard Model and Higgs working group: Summary report, hep-ph/0604120.
- W. Kilgore, The status of Higgs physics, AIP Conf. Proc. 753:309-322, 2005.
- T. Krupovnickas et al., Exploring the BWCA (bino-wino co-annihilation) scenario for neutralino dark matter, hep-ph/0511034.
- T. Krupovnickas et al., Model independent approach to focus point supersymmetry: From dark matter to collider searches, hep-ph/0507282.
- W. Marciano et al., Status of the Cabibbo angle, hep-ph/0512039.
- W. Marciano and A. Sirlin, Improved calculation of electroweak radiative corrections and the value of $V(u,d)$, hep-ph/0510099.
- W. Marciano et al., Physics at a Fermilab proton driver, hep-ex/0509019.
- W. Marciano, Tau 2004: Summary / commentary, Nucl. Phys. Proc. Suppl. 144:359-366, 2005.

W. Marciano, Electrons are not ambidextrous, Nature 435:437-438, 2005.

W. Marciano, Long baseline neutrino oscillations and leptonic CP violation, Nud. Phys. Proc. Suppl.138:370-375, 2005.

E. Scholz et al., Numerical simulations with two flavors of twisted-mass Wilson quarks and DBW2 gauge action, hep-lat/0512017.

E. Scholz et al., $N(f) = 2$ lattice QCD and chiral perturbation theory, hep-lat/0511036.

E. Scholz et al., Dynamical twisted mass fermions, hep-lat/0509131.

E. Scholz et al., Twisted mass fermions: Neutral pion masses from disconnected contributions, hep-lat/0509036.

E. Scholz, Light quark fields in QCD: Numerical simulations and chiral perturbation theory, DESY-THESIS-2005-023, Jul 2005. 125pp.

E. Scholz et al., Lattice spacing dependence of the first order phase transition for dynamical twisted mass fermions, hep-lat/0506025.

E. Scholz, Updating algorithms with multi-step stochastic correction, hep-lat/0506006.

A. Sori et al., Linear collider physics in the new millennium. Singapore: World Scientific (2005) 499 p, (Advanced series on directions in high energy physics 19.)

A. Sori et al., Systematic effects of the quenched approximation on the strong penguin contribution to ϵ'/ϵ , hep-lat/0603025.

A. Sori et al., Angles from B Decays with Charm, hep-ph/0603019.

A. Sori et al., Calculation of the neutron electric dipole moment with two dynamical flavors of domain wall fermions, hep-lat/0512004.

A. Sori et al., Massive neutrinos in a grounds-up approach, hep-ph/0511282.

A. Sori et al., 'Seesawing' away the hierarchy problem, hep-ph/0511281.

A. Sori, D. Suprun, Determination of γ from charmless $B^+ \rightarrow M^0 M^+$ decays using U-spin, hep-ph/0511012.

A. Sori, J. Zupan, Semi-inclusive hadronic B decays as null tests of the standard model, hep-ph/0510325.

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A. Soni et al., Neutron electric dipole moment with two flavors of domain wall fermions, PoS LAT2005:010,2005.

A. Soni et al., $K(l3)$ form-factor with two-flavors of dynamical domain-wall quarks, hep-lat/0510018.

A. Soni, CP violation highlights: Circa 2005, hep-ph/0509180.

A. Soni et al., The Kaon B-parameter from quenched domain-wall QCD, hep-lat/0508011.

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D. Suprun, $B \rightarrow \pi K$ puzzle: Solutions in the standard model and in new physics, AIP Conf.Proc.805:318-321,2006